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Measurement of cut front properties in laser cutting

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Abstract

Cut-front properties are a key variable in laser-cutting and thus of major importance for self-optimization. Within the Cluster of Excellence at RWTH Aachen University, several achievements were made in setting up sensor-systems that provide information on the operating-point of this melt-based manufacturing process. These achievements contribute to a gradual increase in system-transparency which is seen as an enabler for self-optimization.

Instead of searching for a single measurand to characterize the course of the process, an approach is being presented which establishes a surrogate criterion to allow determination of the current operating-point. In the depicted area, this is done by joining sources of information from process observation, determining boundary-conditions such as actual feed-rate and modeling of process-variables. Although process-variables like properties of the cutting-front are influenced through more than one process parameter, a concept for a sensor-system is reported showing the correlation between properties of the melt-front and the current feed-rate. The results are compared to a solution derived from process-simulation.

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1. Introduction

Laser cutting is used in several areas of manufacturing as in processing of flat metal sheets for construction, cutting of pre-formed parts in the white goods industry or trimming of hardened 3D parts in the automotive sector. All these variants require a reliable cutting performance, some with special requirements to cut face roughness, some with the need for dross free processing results. Common to all of them is the strive for both maximum cut length per time at full separation. Today, cutting machines operate with setting parameters which offer a stable process window accounting for the most relevant disturbances that might occur during processing of material in a real world scenario. From a scientific point of view, it is of major interest to establish a feature which qualifies the current operating point of a laser cutting process which at the same time can be associated to a process model. Research on contributions towards self-optimizing manufacturing systems has already shown first results (Thombansen et al., 2012).

Several approaches have been reported which focused on acquiring signals of the process which are relevant to the processing result (Chen, 1997) (De Keuster et al., 2007). All of these have added to process understanding but differ in applicability to industrial systems. In normal operation of a laser cutting system, coaxial process observation can be introduced without interfering with the process or with the performance of such a machine. With coaxial illumination of the interaction zone, it allows to acquire information about geometric properties of the cut during processing namely the melting point. This feature can also be quantified by modeling making it an ideal feature to determine the operating point. As such, it contributes to the advance towards a self-optimizing laser cutting system.

2. Approach

The position of the melting point can be qualified twofold, theoretically by a process model and practically by a process observation system (Thombansen et al., 2013). As both solutions provide results on a different physical scale, a surrogate criterion has to be established which links both solutions to such an extent that control can be executed.

On the side of the process model, the absorption of the laser beam is used to establish a physical balance based on the beam caustic, the absorption of the material and the feed rate. Based on the Stefan Signorini condition, a two dimensional model is applied which leads to a description of the geometric shape of the melt front. This shape is used to establish the surrogate criterion.

From the coaxial perspective, the surface of the metal sheet can be observed resulting in an image of the sheet with the cut. Illuminating the surface and capturing the reflection by means of a high speed camera allows determining areas with reflection from metal sheet surface, and areas without reflection – the kerf. The intensity distribution in the image is used to establish the surrogate criterion from the side of the process observation.

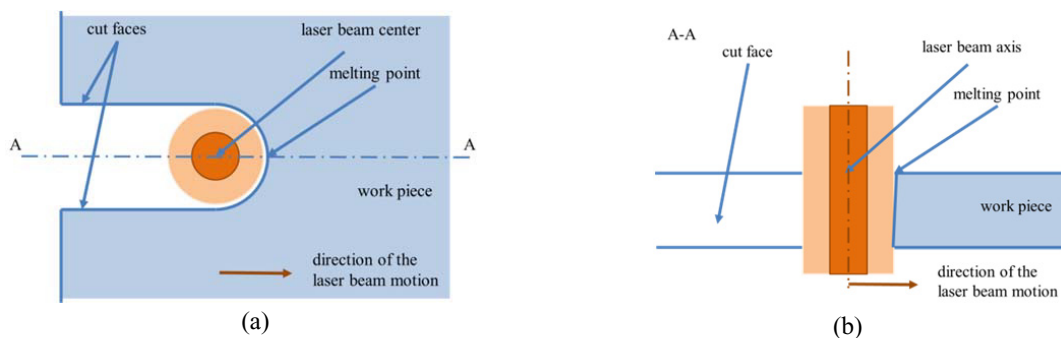


Fig. 1. Sketch describing the position of the melting point (a) top view; (b) cross cut at A-A.

The experiments were conducted with a CO₂ laser at 3kW with a f250 lens cutting 5 mm stainless steel.

Table 1. Setting parameters for the experiments.

Setting Parameter	Value
Feed rate	900, 1200, 1500, 1800, 2100, 2400 mm/min
Laser power	3.000 Watts
Focal length	250 mm
Focus positions	-2, -4, -6 mm
Material	Stainless steel 1.4301
Thickness	5 mm

3. Description of the physical model to determine the melting point

The position of the melting point is modeled as follows. In the plane positioned in the middle of the cut kerf and oriented by the feed direction and the direction perpendicular to the upper surface of the work piece, the so called sagittal plane, the dynamic of the molten material is described by the motion of its free boundaries. The latter are the absorption front of the melt at the transition to the gaseous phase, where the laser energy is deposited, and the melting front at the transition to the solid phase, where the material is molten.

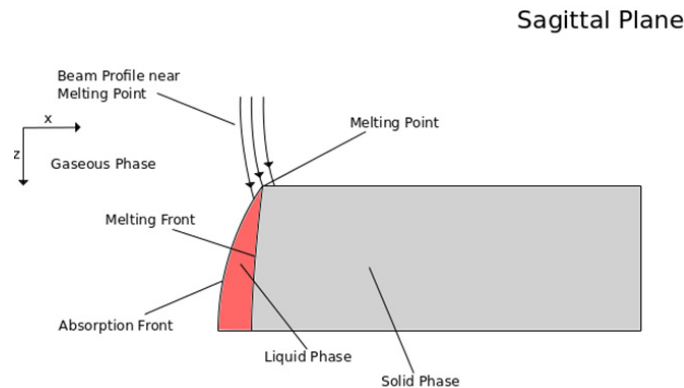


Fig. 2. Sketch of the physical model used to determine the melting point.

The intersection point of the upper side of the work piece and the melting front is the first point, where the material melts. Here, the absorption front and the melting front intersect resulting in a negligible melt film thickness. This point is called the melting point. To determine its position, the motion of the melting front at its upper point has to be considered. The motion of the melting front is determined by the energy conservation. The difference between the heat flux inside the liquid phase and the solid phase at the melting front is given by the energy needed to melt up the appropriate material volume (Vossen et al., 2013) (Poprawe et al., 2010). This energy conservation can be expressed by the so called Stefan-Signorini-Condition:

$$\rho v_p H_m = q_l - q_s$$

With the density ρ , the velocity of the melting front in normal direction v_p , the specific melting enthalpy H_m and the heat fluxes in the liquid and solid q_l, q_s state.

At the upper side of the work piece, there exist no melt and the heat flux q_l is given by the heat flux introduced by the laser beam:

$$q_l = I(x, z_{upper})\mu A(\mu)$$

With the intensity distribution at the upper side of the work piece I (x denotes the coordinate along the upper surface of the work piece, z denotes the coordinate perpendicular to the x -direction, z_{upper} denotes the value of z at the upper side of the work piece), the cosine of the angle between the Poynting vector and the normal direction of the surface of the work piece μ and the absorption factor A .

In the stationary state, the velocity v_p at the melting point is given by the feed velocity v_0 and the heat flux q_s can be approximated by $v_0\Delta T/\rho c_p$

In this case, the Stefan-Signorini-Condition at the upper side of the work piece is of the form:

$$\rho v_0 H_m = I(x, z_{upper})\mu A(\mu) - v_0\Delta T/\rho c_p$$

with the difference between the melting temperature and the temperature of the environment ΔT and the specific heat capacity c_p . For known material parameters, intensity distribution and beam profile, the only remaining unknown is the x -coordinate. The values for x , that solve the last equation denote possible melting points (the solution is not imperatively unique, depending on the beam properties).

4. Process Observation

The process observation is realized by combining and separating the optical path depending on the respective wavelength (Kratzsch et al., 2000). The processing radiation of the CO₂ laser is at 10.6 μm while the observation wavelength is at 808 nm. The beam splitter for this task is coated to reflect the CO₂ radiation and to transmit the observation wavelengths. Laser source emitting at 808 nm is coupled into the optical system to illuminate the surface of the work piece. After exiting the fiber, the light is being collimated, transmitted through the beam splitter and focused to the work piece by the focusing lens of the cut head. The reflection from this surface is relayed to the camera system by the focusing lens of the cut head and a specially designed optical system which realizes a magnified image on the camera. (Thombansen et al., 2012)

The image from the camera is transferred to a standard computer through a frame grabber, storing the images at a rate of 4 kHz to a fast hard disk array. Currently, the processing of the images is done in software offline after cutting to establish the searched criterion.

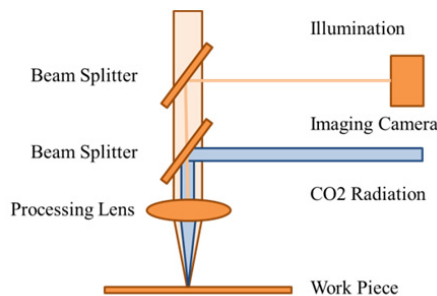


Fig. 3. Coaxial setup of the beam splitter for process observation.

Image (a) shows the intensity distribution which is received from the surface with the structure of the metal sheet and the cut kerf from bottom to top. The roughness of the sheet surface leads to a coarse intensity distribution in the

image. To prepare the data for evaluation, morphological image processing algorithms are applied to equalize the intensity in the area where no cut kerf exists. An ‘open’ function with a disc radius of twelve pixels is applied and summed to the original image to produce image (b). Visual inspection of the image allows the determination of the head of the cut kerf as a continuous drop in intensity.

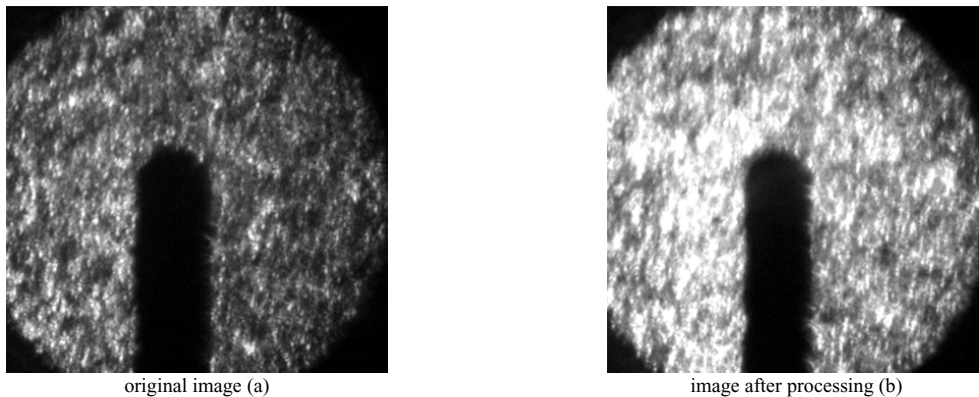


Fig. 4. Image from the process observation and image after application of algorithms (288 x 300 pixels at 8 bit).

As the melting point is on the axis through the center of the kerf, the image processing uses the columns in the vicinity of the centerline to establish an intensity profile. It does so by summing the intensities of the camera pixels perpendicular to the centerline for the closest ten lines. The resulting profile in image (c) shows the intensities over the position. In the graph, position zero represents the top of the image.

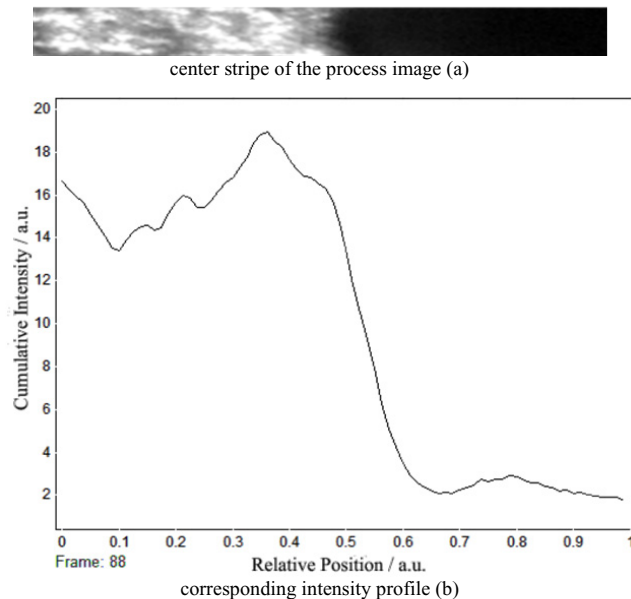


Fig. 5. Evaluated area of the image and resulting intensity profile.

5. Analysis and results from experiment and simulation

Defining the melting point as that position in feed direction which melts first is trivial. Establishing criteria in modeling and process observation however imposes the problem that such criteria have to be based on different physical properties which can either be measured or evaluated.

In modeling, the criterion is established by neglecting the melt film thickness and assuming the incident angle of the radiation to be at about 87 degrees. Based on the model as it is described above, values for the distance of the melting point from the laser axis are calculated for the focus positions 0, -1.73, -4.3 and -6.02 mm. The resulting values are plotted below.

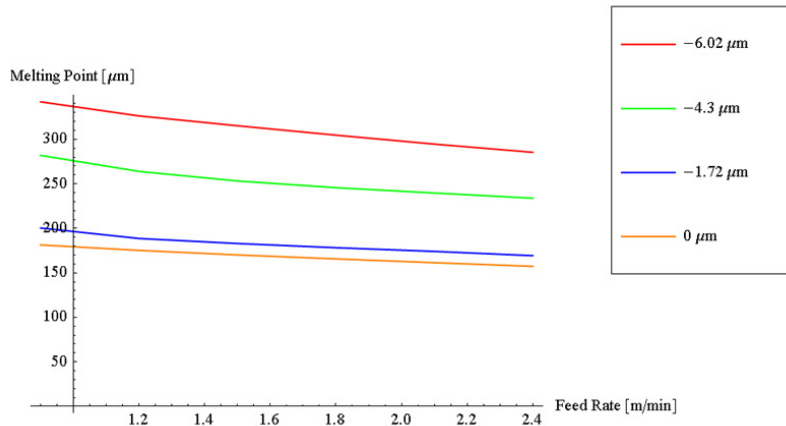


Fig. 6. Distance of the melting point from the laser axis over feed rate for different focus positions.

In the experiment, the criterion is established by a threshold in the intensity distribution assuming that the shape of the cut front at the top of the metal sheet leads to consistent changes in reflectivity of the metal sheet surface. Based on this assumption, images from process observation are evaluated for experiments with the focus position 0, -2, -4 and -6. As the evaluation is based on measuring positions of the melting point for different setting parameters, distances relative to some arbitrary position are given in the table.

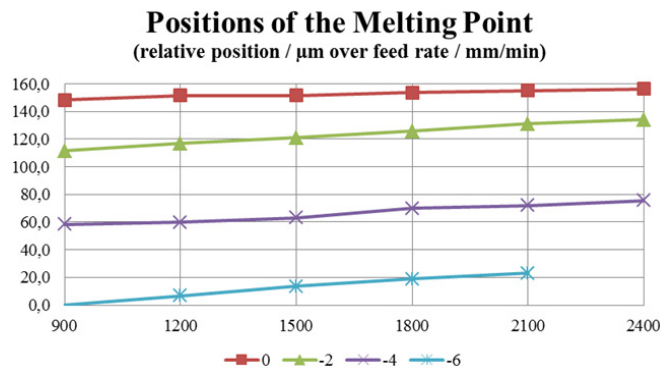


Fig. 7. Measured position of the melting point over feed rate for different focus positions.

6. Discussion

The analysis shows the results from two different criteria which both have been established in their context to the best expert knowledge. They are linked to each other by describing the same process property which is the first position in feeding direction which is affected by the laser cutting process. Although the evaluation of both criteria is based on different physical principles, both provide the same characteristics. It has to be noted, that the focal planes in the simulation are based on a measured intensity distribution which is only known at the denoted z positions. In the experiment, the focal planes could only be set to discrete steps at millimeter resolution. This might cater for some differences in absolute values.

On the path to self-optimization of manufacturing systems, cognition of technical systems stands in the focus of research. If a laser cutting machine is capable of determining its current operating point autonomously, it may correct deviations from the intended course of the process autonomously, too. On this path, links between modeled behavior of the process and measured results are needed to select corrective measures.

The report shows that a surrogate criterion has been established which links process modeling to process observation.

Acknowledgements

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